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Technical note

Freeze-proof method and test verification of a cold region tunnel employing electric heat tracing

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ABSTRACT

In recent decades, numerous tunnels have been built in the cold region of China. However, frost damage occurs frequently inside the tunnels; this damage threatens the stability of the tunnels. In order to prevent frost damage, a method employing electric heat tracing (EHT) was presented in this study. Moreover, the EHT-based freeze-proof system layout and installation procedures were also introduced. The tunnel liner EHT system is composed of four parts: heating cable, insulation layer, protective layer and fire protection layer. This EHT system was adopted in the Dongnanli highway tunnel (located in northeastern China) to verify its applicability. In-situ test results indicated that the temperature behind the liner begins to heat up after one hour of electrifying the system; next, the temperature becomes positive and remains stable after three hours of electrifying the system. The operation of the heating system is quite stable, and the insulation effect is significant. Through the assessments of the heating efficiency that is required to reach the target temperature and a constant temperature heating effect, it is suggested that the combination of thermal insulation and electric heat tracing is feasible and effective in preventing frost damage in tunnels. The research results provide references for the design and construction of frost prevention systems in tunnels in cold regions.

1. Introduction

Permafrost regions account for approximately 23% of the Earth's surface and are primarily observed in Russia, Canada, China and the United States state of Alaska (Fordl et al., 2010). Seasonal frozen-ground regions account for approximately 53.5% of the total land area in China. Generally, when the frost heave occurs as a result of low temperatures, the properties of a rock mass change, and the frost deformation significantly affects the tunnel stability. Tunnels in these cold regions usually suffer from frost damage (Fig. 1), such as peeling, liner surface fractures, seepage, icing, slippery collapse and tunnel freeing port freezing induced by freeze-thaw cycles (Mimouni et al., 2014; Zhao and Cai, 2001; Lai et al., 2015a, 2016); substantial manpower, material and financial resources are required to address these damages (Zhu et al., 2010; Li et al., 2015).

Different heat prevention and freeze-proof measures are used to reduce frost damage in cold region tunnels (Johansen et al., 1988; Guidice et al., 1978). Traditional passive freeze-proof measures include a thermal insulating ditch, a thermal insulating door (Lai et al., 1998, 1999), an antifreeze thermal insulating layer (Inokuma, 1996), etc. Light insulation materials are usually used to reduce the freezing area of a rock mass (Lai et al., 2003; Takumi et al., 2008). It has been reported that the required thickness of the thermal insulation layer increased as the ambient temperature decreased (Lai et al., 2000); however, the freeze-proof effect does not increase when the thickness reaches a certain value, and the thermal insulation layer cannot be infinitely thickened. The installation of the thermal insulating doors would inevitably affect tunnel operation, especially in the case of high traffic flow. For high-speed railway and expressway tunnels, it is practically impossible to close the thermal insulating doors. Therefore, these traditional measures are not available in extremely cold regions (Zhang et al., 2004a, 2004b, 2007). Insulation materials can reduce or prevent thermal propagation and decrease the freezing rate; however, the freeze-proof effect is not good enough. Thus, active heating freeze-proof measures, including ground heat exchanger pump technology (GHEP) (Jacovides and Mihalakakou, 1995; Balbay and Esen, 2010) and electric heat tracing technology (EHT) have also been developed in recent decades. Tunnel liner ground heat exchangers (GHEs) were applied for the first time in station rooms of Vienna Metro for both heating and cooling purposes (Brandl, 2006). Adam and Markiewicz (2009) gave one

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Fig. 1. Frost damages in cold region tunnels (Chen, 2004).

possible method for the economical optimization of tunnel liner ground heat exchanger (GHEs) with a finite element simulation model. Simultaneously, a horizontal U-tube (HUT) road heating system was developed using tunnel ground heat that took advantage of HUTs that were embedded in the shallow ground of the central part of an inverted tunnel for heat extraction (Islam et al., 2006). Recently, an innovative tunnel liner GHE heating system was introduced using heat pipe technology in the Linchang Tunnel of Inner Mongolia, China (Zhang et al., 2013, 2014, 2016). This type of system utilized the tunnel liners as a heat exchanger to extract geothermal energy from the rock mass in the middle part of the tunnel for the heat tunnel liner and the drainage system at the tunnel entrance. However, complex construction and large investment at the beginning limited the development of a ground source heat pump system (Konrad and Morgenstern, 1980; Kozlowski, 2003; Krabbenhoft et al., 2007). Recently, the low-temperature radiant electro thermal cable heating system has been widely implemented in airports, gymnasia, and large residential quarters because of its economic characteristics in engineering construction and operation (Li et al., 2002; Kawamura et al., 2008) and also achieved good performance in a tunnel portal heated snow-melting pavement system (Lai et al., 2015b). At present, considering that the existing freeze-proof methods are not sufficient to provide heat insulation and freeze-proofing at tunnel entrances, a heat-insulation, freeze-proof, cost-effective, and environmentally friendly tunnel frost damage prevention system is required (Lee et al., 2012). The combination of EHT and thermal insulation is proposed in this study; this combination can provide new ideas for the design and construction of frost prevention systems in cold region tunnels.

2. Tunnel liner EHT system

The electric heat tracing system is a radiant heating system that transforms electric energy into thermal energy by electrifying the heating cable and subsequently transferring the thermal energy to the tunnel. The heating cable (c.f. Fig. 2) is mainly composed of seven elements: core wire, insulation layer, inner jacket, heating thread, outer jacket, braided layer and reinforce layer. The self-limiting temperature heating belt that is generally used in the current has electrical resistivity with a high positive temperature coefficient (PTC). Generally, PTC materials have a remarkable resistivity-temperature characteristic (R-T characteristic) that can be used for constant temperature heating and adjustment. PTC materials can transform electric energy into thermal energy; additionally, the electrical resistivity increases gradually as temperature increases. When the temperature of the core belt reaches a certain value (the maximum temperature) the electric resistivity will be high enough to block the current. At this point, the temperature of the heating element will enter a constant-temperature state. Consequently, by repeating the above process, the heating

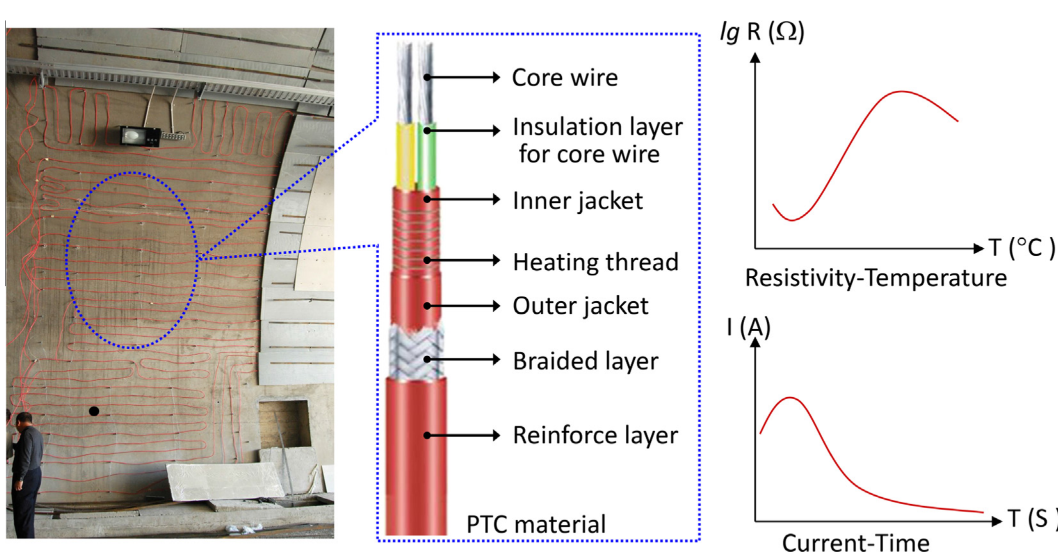

Fig. 2. Heating cable composition and characteristic of PTC material.